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TITLE: TRANSLATION OF FIELD-REVERSED CONFIGURATIONS IN THE FRX-C/T EXPERIMENT

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TRANSLATION OF FIELD-REVERSED CONFIGURATIONS IN THE FRX-C/T EXPERIMENT*

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I. INTRODUCTION: One of the unique features inherent to compact toroids is the potential ability to translate the plasma along its geometric axis. CT translation has proven useful in reactor design studies[1-3], and has been the focus of several experimental investigations.[4-7] In this paper, we report on the initial results from translation experiments performed with the field-reversed configuration (FRC) plasmas generated in the FRX-C/T device.

II. EXPERIMENTAL CONFIGURATION: During 1983 the field-reversed θ-pinch experiment FRX-C[8] was modified in order to study FRC translation. A schematic diagram depicting the new apparatus, renamed FRX-C/T, is shown in Fig. 1. FRC's are formed in a localized D_2 gas cloud injected from a puff valve mounted at the upstream end of the device. A flux-excluding aluminum plate, located approximately 15-cm upstream of the θ-pinch coil, is used to help symmetrize the field line reconnection during FRC formation. The FRC is translated out of the source by application of a small B-field

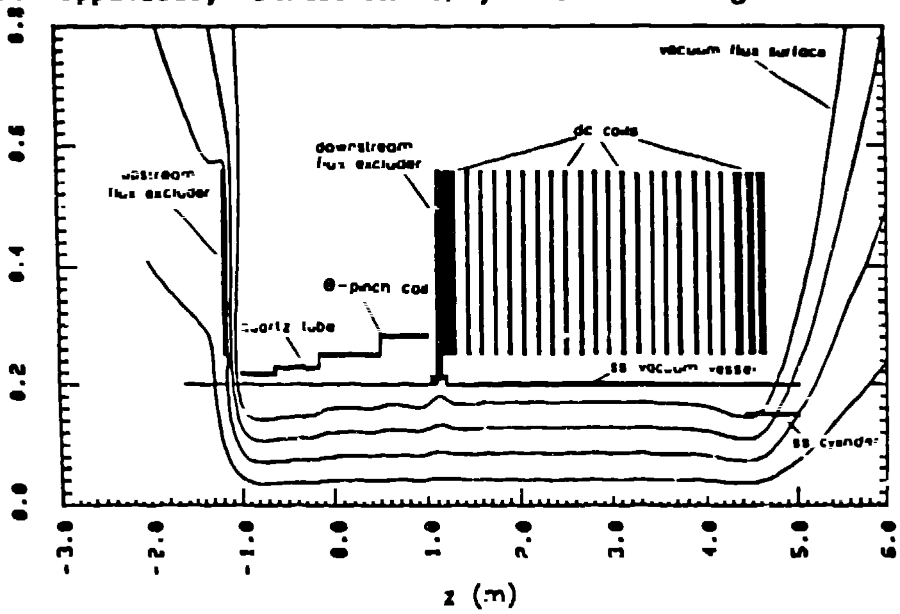


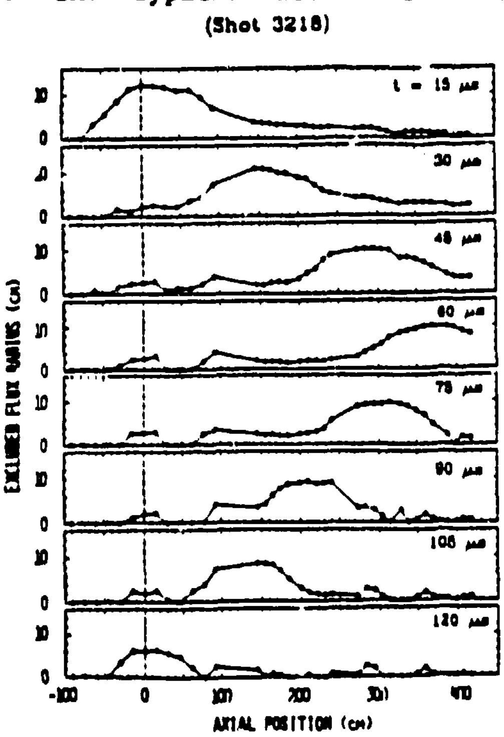
Fig. 1: Schematic diagram of the FRX-C/T experiment.

gradient, formed by a slight taper in the θ-pinch coil. The plasmas are currently being launched into a 4-m-long, 0.4-m-ID, stainless steel vacuum chamber that contains up to an 8-kG solenoid guide field. A 15-cm gap separates the θ-pinch coil from this translation region. Typical vacuum field flux surfaces are also plotted in Fig. 1. The vacuum B_z field on axis varies by no more than 8% at the pinch guide field coil interface. The guide field magnets are energized using a 2.5-MW dc power supply. These dc components act in effect as a "power crowbar", a highly desirable system since FRCs have been generated with lifetimes exceeding the 250-μs decay time of the pulsed θ-pinch coil B-fields.[9] At the downstream end, a mirror field designed to reflect the FRC is formed by a combination of dc coils and plasma induced image currents in a 0.6-m-long, 0.3-m-diameter metallic cylinder.

Present diagnostics include an array of 42 external magnetic probes, two flux loops, and five chords of side-on interferometry. The metallic vacuum chamber and low voltage (<0.3 kV) technology associated with the translation region is compatible with several new in-vacuum diagnostics (e.g., soft x-ray detectors) that have been found difficult to implement on the θ-pinch. The internal B-field components of the translating plasma are also measured.[10]

III. EXPERIMENTAL RESULTS: Plotted in Fig. 2 are the measured excluded flux radius profiles $r_{\Delta\Phi}(z)$ for seven different times. The axial position z=0 denotes the center of the θ-pinch coil. The main capacitor bank is discharged at time t=0. These data were taken using a 5-mtorr D_2 puff and a vacuum B_z-field of 4 kG, measured in the downstream end of the θ-pinch and into the translation region. An FRC is formed in the θ-pinch coil with separatrix radius $r_s \approx r_{\Delta\phi} \approx 10$ cm and length $\ell_s \approx 150$ cm. The plasma resides in the θ-pinch coil for approximately 10 μs. Between times t = 10 and 20 μs the FRC is accelerated to the average axial velocity $v_z \approx 8$ cm/μs. The plasma enters the translation section (z>115 cm) without appreciable internal flux and particle loss and reaches the downstream mirror at time t≈60 μs. The FRC is reflected from the mirror and propagates back toward the source with an average velocity v_z = -7 cm/μs. Including the return transit, the FRC traverses an axial length of about 800-cm. The inferred internal poloidal magnetic flux decay time, τ_Φ = 115 μs, is comparable to that observed in stationary plasmas with similar parameters. Generation of the reversed magnetic field inside the major radius $R = r_s/\sqrt{2}$ has been confirmed by internal magetic probe measurements[10] of the B-field.

FRC translation is further examined using the five chords of side-on interferometry. The chords are located at positions z = -20, 20, 60, 184, and 428 cm. Typical data are shown in Fig. 3. The line averaged density



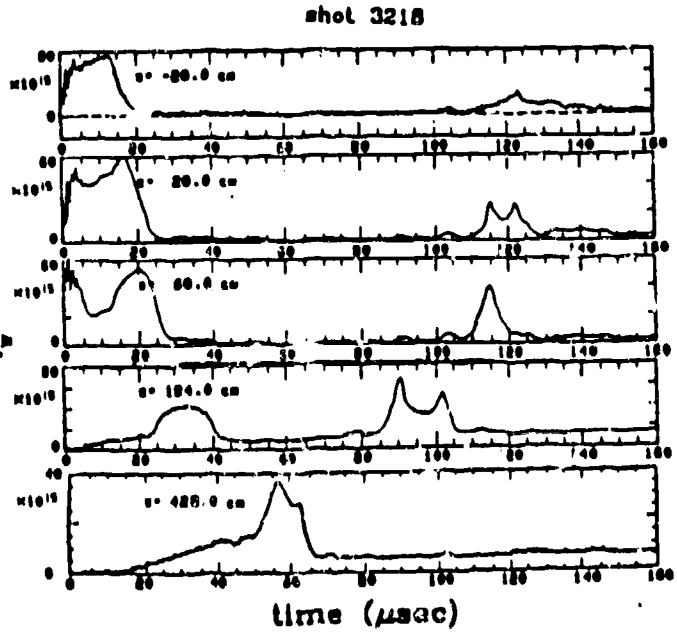


Fig. 2: Excluded flux radius profiles $r_{\Delta\phi}(z)$ plotted at 15-μsec intervals, showing FRC translation and reflection off of downstream mirror.

Fig. 3: Time dependent electron density data for a translating FRC from 5 chords of interferometry that span 4.5-m of the device.

$\bar{n}_e = \int_0^{r_w} n dr/r_s \approx 10^{15}\ cm^{-3}$ is observed to propagate commensurate with the excluded flux profile for the same shot shown in Fig. 2. The particle inventory, estimated during translation using interferometry and magnetic probes (see Sec. IV) is 4×10^{19}. The oscillations in $\int n dr$ observed in the reflected plasma are evidence of the n=2 rotational instability. (Presence of the n=2 instability is confirmed by stereoscopic measurements made along orthogonal chords with the interferometer and a continuum radiation monitor.) The stable period prior to the onset of this mode, $\tau_s \approx 60$ μs, is about equal to that observed for stationary plasmas with similar $\bar{n}_e$, r_s, and B.

A parameter of importance for FRC equilibrium and transport physics is x_s, the ratio of r_s to the flux conserving wall radius r_w. Values of x_s in the θ-pinch source are currently limited to about 0.55. However, x_s can be increased substantially by allowing the translating plasma to expand against a reduced guide field. Figure 4 displays $r_{\Delta\Phi}$ profiles inside the translation region for three consecutive shots where the vacuum guide field was set at (a) 1.5, (b) 1.0, and (c) 0.5 kG. The observed values of x_s are 0.6, 0.7, and 0.8, respectively. In all cases, a reversed B_z-field is observed on axis.[10] The line-average densities are: (a) 3.3, (b) 2.3, and (c) 1.6×10^{14} cm^{-3}. The corresponding total temperatures from pressure balance are: (a) 340, (b) 300, and (c) 190 eV (±20%). Values of v_z are found to increase with larger x_s due to the stronger accelerating B-field gradients at the transition. The magnitude of the downstream mirror is insufficient to reflect these faster moving, expanded plasmas.

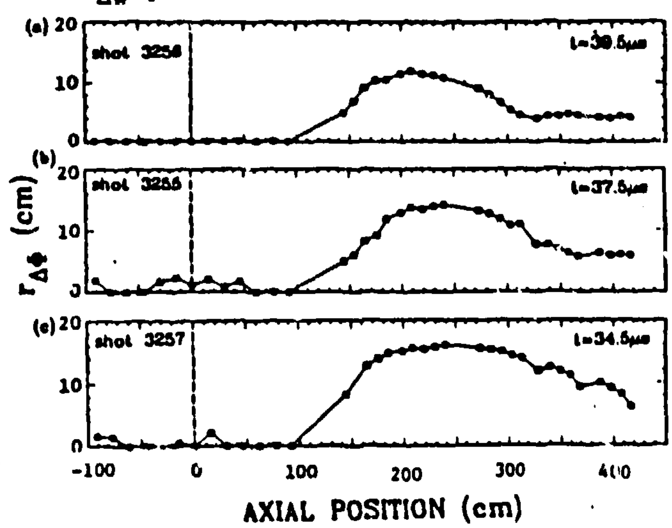


Fig. 4: Generation of large x_s FRCs in FRX-C/T. Excluded flux radius profiles for x_s values of (a) 0.6; (b) 0.7; (c) 0.8, generated on 3 consecutive shots.

At higher magnetic fields (vacuum $B_z \approx 7$ kG), FRCs with $\bar{n}_e \approx 1.6\times10^{15}$ cm^{-3} are observed to translate at faster speeds, $v_z \approx 15$ cm/μs. The plasmas enter the guide field region with negligible flux loss. The n=2 instability is often detected before the FRC reflects from the downstream mirror. FRCs have also been generated at higher fill pressures (15 mtorr); however, a rapid axial expansion occurs before these plasmas are accelerated out of the source.

IV. DISCUSSION: In these experiments on FRX-C/T, FRC plasmas have been formed using puff gas injection and a slightly conical θ-pinch coil. Formation and acceleration of the FRC out of the source occur in two distinct steps, separated by 5-20 μs. At 5 mtorr conditions using matched θ-pinch and dc guide fields, the plasma translates at speeds 40-60% of the Alfven speed. This corresponds to an axial kinetic energy 4-10% of the plasma thermal energy. No abnormal flux loss or disruptive dynamics are observed, even though the plasma moves past an abrupt transition in the flux conserving wall (r_w=28 to r_w=20 cm with a 15-cm insulating gap). On occasion, however, tearing of the plasma near this interface is observed when the plasma is allowed to expand against a reduced guide field.[10] Exceptionally large x_s values (0.8) have been generated by expansion of the plasma in the translation region. The corresponding S ($=R/\rho_i$) values are 10-11 while $\bar{s} = x_s S/5$ ranges between 1.1 and 1.7. The FRC volume V, length ℓ_s, external magnetic field B_w and peak density n_m for these translating plasmas before and after expansion have been compared with adiabatic theory.[11] (The theory assumes no losses or translational energy.) For $\gamma=5/3$ and diffuse radial profile[11] $\varepsilon=-1/4$ the measured ℓ_s (and therefore V) increases less rapidly with increasing x_s than theory predicts. B_w decreases with x_s in approximate agreement with theory, while n_m decreases less rapidly. Taking into account energy losses during translation brings theory and experiment into closer agreement. Comparison with theory assuming $\gamma=1$ shows poorer agreement.

A practical benefit gained by translation is that every side-on diagnostic views the entire plasma length as the FRC moves by. Assuming that the FRC equilibrium remains unchanged during its transit past a diagnostic, the time-dependent data from each diagnostic can be converted to an axial profile, provided v_z is known. The data from a single external B-field probe and chord of interferometry have been combined to estimate the total particle inventory of the moving FRC.

Translation has been modeled theoretically with a 2-D MHD code,[12,13] modified specifically for FRX-C/T conditions. Simulations have been performed for the 5-mtorr, 7-kG vacuum B_z case; however, the effects from the upstream flux excluder are not included, and a slightly different initial axial gas distribution and θ-pinch coil configuration are assumed. The code results are in qualitative agreement with experimental observations. The FRC acceleration times are comparable while the predicted v_z values are about 2/3 of that observed. The calculated evolution of r_s and ℓ_s along the FRC trajectory is in reasonable agreement (20%) with that observed. The code also predicts that an open field line precursor plasma preceed the FRC. Indeed this plasma is observed (see Fig. 3 and Ref. 10). More detailed modeling including the precise experimental conditions is planned.

Qualitatively different behavior is observed at higher D_2 puff gas pressures. At 15-mtorr, the rapid axial plasma expansion towards the downstream end is observed prior to the acceleration of the plasma. This expansion is not fully understood. Additional experiments to further explore these higher pressure regimes are planned.

The n=2 instability is observed in the translation region and the stable period τ_s appears to be relatively unaffected by translation. τ_s is also the typical time when the FRC reaches the downstream mirror. A multipole magnetic field is known to stabilize this mode.[14,15,9] A dc quadrupole system is currently being prepared for implementation on FRX-C/T. Additional near term experimental objectives will concentrate on assessing the particle and energy confinement times for these plasmas. In particular contributions from impurity line radiation will be the focus of several new diagnostics: bolometry, VUV and grazing incidence spectroscopy, and bremsstrahlung continuum measurements.

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